2017 OFR Demonstration Site Monitoring and Analyses:

Effects on soil hydrology and salinity, and potential implications on soil oxygen

Final

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Executive Summary

On-farm recharge (OFR) is a practice that uses surface water to alleviate demand on and replenish groundwater supplies. It can take on two forms: *in lieu* recharge and direct recharge. *In lieu* recharge utilizes surface water supplies instead of groundwater to irrigate crops. Direct recharge applies water beyond the needs of the crop and replenishes the groundwater supply.

Floodwater application reduces oxygen diffusion to soil pores because 1) ponded water forms a diffusion barrier; and 2) greater water content decreases connectivity between soil pores. Low oxygen levels in soil can inhibit plant respiration and growth. Normal oxygen partial pressure is 20.95 kPa. Based on past studies of tree crops, two threshold oxygen levels were selected: above 10 kPa, as optimal for the studied nut crops, and below 5 kPa, a level that may adversely affect crop growth and health.

The present study examined OFR with grapes, walnuts, and pistachios at six sites in the San Joaquin Valley, plus one additional site from a previous study, also in the San Joaquin Valley. Each site was comprised of a recharge plot that received direct recharge paired with a control plot with the same crop and soil characteristics, but meant to receive *in lieu* recharge (via the flood system) or drip application with groundwater. At the end of the 2017 recharge demonstration, however, three control plots had also received direct recharge from water applications that exceeded the crop’s water demand. At another site, both control and test plots had only received *in lieu* recharge due to limited surface water amounts or the host growers’ more conservative volume of water application.

Instruments were installed at all sites to continuously measure field surface water depth and soil moisture (i.e. volumetric water content, VWC) at multiple depths through the soil profile. Oxygen levels were also measured at four plots (recharge pistachio, almond, and walnut plots, and a control almond plot). These instruments did not capture conditions for all 2017 OFR events because OFR had begun in the first quarter of 2017 at some locations before instrument installation, which took place in the second quarter of 2017.

OFR Hydrology and Chemistry

Nine plots received OFR between February and November 2017, with total volumes applied (as documented by growers) ranging from 0.6 to 10 ac-ft/ac (7.1 to 119.6 inches). The wide range of application volumes reflect both water availability and grower’s comfort level in applying water for recharge, given their permanent crop type.

Direct and *in lieu* recharge was calculated using a water budget, correcting for ETc and precipitation, and by determining the beginning of direct recharge by the measurement of field capacity (FC) in the soil.

The water applications resulted in *in lieu* recharge of 0 to 27.5 inches and direct recharge ranging from 0 to 113 inches. Mean infiltration rates ranged from 2 to 7 inches/day. The higher rate of 7 inches/day was estimated for a site classified as somewhat excessively drained by NRCS; it is notable that a relatively high rate of 3.5 inches/day was observed at a plot identified as “somewhat poorly drained” by NRCS. One walnut plot experienced declining infiltration rates from 3.4 inches/day in June to 1 inch/day in

October. This phenomenon did not occur elsewhere in this study but had been observed in an earlier OFR demonstration study at a ranch in Fresno County.

Up to 24 hours were required for water to travel from ground surface to below the root zone. Direct measurements of soil salinity at paired sites using moisture probes showed an average volumetric ion content (VIC) decline by about 2 to 3%. This decline is much less than direct measurements of salt decline (total dissolved solids, TDS) in other studies using soil core samples, raising questions regarding the efficacy of measuring pore water salts using VIC moisture probes' measurements.

Soil Oxygen

Soil oxygen was measured to understand the potential implications of OFR on oxygen levels in the pore space. The soil oxygen response was studied for direct or *in lieu* recharge and for drip application of groundwater. Correlation analysis included the season, depth, number of water applications and their duration, oxygen depletion rate, elapsed time where VWC exceeded 74%, minimum oxygen level achieved, and the duration soil oxygen levels were between 5 and 10 kPa.

The analyses did not provide a simple rule of thumb or algorithm describing the relationship of soil moisture and soil oxygen depletion. It was common under both drip and floodwater application events for shallow (10 inches) and mid (18 inches) depth soils to drop below 10 kPa, though this occurrence was uncommon for deeper (26 inches) depth soils. Oxygen depletion rates were generally greater in shallower than deeper soils, and in the summer than the fall, suggesting a greater density of respiring roots at shallower depths and seasonally more active root respiration in the summer.

We analyzed several variables as possible drivers triggering soil oxygen response and declines. We did not find a relationship with temperature or soil texture. The lack of correlations may be due to relatively similar temperatures and soil textures recorded through this study. Maximum surface water depth correlated with minimum oxygen levels for all depths and season. We found oxygen levels below 10 kPa were generally associated with percent saturation of 74% or greater, though significant variance is associated with that threshold, suggesting other factors affect that trigger for oxygen declines. During the summer, minimum oxygen measurements correlated with oxygen depletion rates, and often correlated with elapsed hours past soil moisture at 74% saturation.

From these above correlations and observations, we are presenting a conceptual model of drivers of soil oxygen levels, consumption and transport as a hypothesis.

- Plant and soil microbe respiration consumes soil oxygen. Microbe presence, root distribution, and time of year determines where and when soil oxygen is consumed.
- Oxygen is replenished through diffusive transport of oxygen from the surface to soil pores across and at depth in the root zone.
- Several factors can limit that diffusive transport.
    - Surface water can provide a barrier preventing diffusion of oxygen into the soil profile.
    - Pore moisture can lead to barriers to pore connectivity and oxygen diffusion across those pore spaces, limiting replenishment pathways and diffusion rates.

- Reduced oxygen in the pore space provides feedback to the plant, reducing local respiration rates by the plant.

A grower's recharge management decisions can affect soil oxygen levels temporally and spatially throughout the root zone. Crop types affect root depth and distribution, affecting respiration and oxygen consumption throughout the profile. Field surface water depth and water application duration both affect oxygen diffusive pathways. Plant dormancy and growth affect respiration rates and thus soil oxygen consumption rates. Indicators to help guide farmers in implementing an OFR program while minimizing low soil oxygen conditions include the following:

- Avoid standing water for longer than 3 to 4 days on one check at one time.
- Avoid percent saturation greater than 77%, the recommended maximum. This condition may be difficult to prevent during recharge.
- Time above 74% (slightly above FC) exceeding 3 days will increase chances of oxygen levels dropping below 10 kPa.
- Finally, soil oxygen data suggests past flood irrigation methods used by a farmer for meeting crop needs may provide useful and reasonable guidelines for developing an OFR program.

Lessons Learned for Future Field Monitoring

Key lessons learned from the study include:

- Install equipment well ahead of planned recharge events, to account for unexpected delays.
- Studies on commercial farms are invaluable, but come with pitfalls, including communication, that need to be accounted for.
- Care needs to be taken in placing equipment relative to field operations and field operations need to be coordinated to accommodate monitoring equipment.
- Field monitoring can only be conducted with sufficient surface water availability, which means research could be delayed significantly while waiting for water.

Limitations and Suggestions for Further Research

The present study only covers one season of recharge. Long-term effects of recharge are not described by the present study and will require further monitoring. Further study is needed of the dynamics of soil oxygen during and after recharge events. Similarly, the fate of the water after it infiltrates past the root zone is not always known and the rate at which recharged water will reach an aquifer is seldom known for deep aquifers. A method to predict the fate of water quickly and broadly would be quite helpful in developing an on-farm recharge strategy. The present study does not look at the effects of recharge on soil biological processes, such as microbial respiration and plant oxygen demand. Further study of the recharge tolerance of specific species and rootstocks, as well as the impact on plant disease, is crucial.

Conclusions

The rates of recharge can be predicted, but further confirmation of methods is needed. The effects of recharge on salinity are still not clear. VIC does not seem to be a good indicator. Similarly, soil drainage class does not always correlate with observed infiltration rates. Drainage class should be used as a guideline, tempered by grower's knowledge. Further soil oxygen observations are needed to understand how soil oxygen content reacts to recharge. Neither surface water temperature nor soil texture correlated to soil oxygen during or after recharge. However, correlations were found between low oxygen levels and water application variables (surface water depth and irrigation duration), soil moisture, and oxygen depletion rate.

Overall, further study of the effect of recharge on soils and plant health is needed. Additionally, continued monitoring and study of commercial sites would be useful to observe the benefits and drawbacks of OFR under real-world conditions.

Introduction

On-Farm Recharge

On-farm recharge (OFR) is the practice of applying surface water to farmland to recharge groundwater. OFR is a tool to achieve sustainable groundwater levels in agricultural areas that rely heavily on groundwater and includes both *in lieu* and direct recharge.

In lieu recharge utilizes surface water to meet demand that would otherwise be met by groundwater extraction to satisfy crop evapotranspiration (ETc) and refill root zone soil. Direct recharge follows when the applied water exceeds crop demand and flushes below the root zone towards groundwater.

While direct recharge increases groundwater storage, *in lieu* recharge reduces groundwater pumping; both direct recharge and *in lieu* recharge help to reduce groundwater level declines.

Soil Oxygen and Plant Health

Oxygen levels in soil during recharge are important to understand so that detrimental effects on crops and plant health can be avoided. Understanding conditions that lead to low oxygen levels can help growers to avoid or limit low oxygen situations.

Partial pressure of oxygen in air with no water vapor is 20.95 kPa (Apogee, 2014). Oxygen in soil pores varies depending on the ability of oxygen to diffuse within the soil and the rate of plant respiration. Partial pressure of oxygen in soil pores drops when the rate of plant and microorganism respiration is greater than the rate of oxygen diffusion from areas of higher oxygen, such as the atmosphere.

Respiration and associated oxygen demand of plant roots and microorganisms are roughly of the same magnitude (Noah, 2018) and tend to be highest during summer. While plants respire all year round, respiration rates are higher during periods of higher photosynthesis (Shiroya, 1966) and temperature (Atkins, 2003), and have been shown to drop during periods of lower oxygen (Noah, 2018). Microbial respiration increases with temperature but also with water content (Noah, 2018). Thus, total soil respiration tends to be highest when soil is moist during warm summer months. When respiration is higher, greater rates of oxygen diffusion are required to keep oxygen levels high.

Flood irrigation reduces oxygen diffusion because ponded water forms a barrier to gaseous diffusion (Noah, 2018). Additionally, diffusion can also be reduced by greater moisture within soil, which reduces the connectivity of pores. Soil at a water content that is inhibiting diffusion will reduce transport of oxygen to adjacent soils. Vadose zone transport models often use volumetric air content (VAC) when calculating oxygen diffusion rates with a critical (low) VAC for which oxygen diffusion cannot occur (Cook, 2013). At that level, there are no interconnected non-water-filled pores to provide a pathway for oxygen diffusion.

Low oxygen levels in soil can affect plants by inhibiting respiration and root growth. Noah (2018), in a summary of research on root respiration and soil aeration, reports oxygen levels, found by various researchers, associated with reducing respiration rates by half within the roots. Half-respiration oxygen concentrations are a common quantifier of tolerance to oxygen deficiencies. This summary indicates that oxygen levels between 0.1 and 12 kPa result in half-respiration rates for cotton, maize, mustard, and onion. Costello (1991) studied the effect of low oxygen for 5 days on oak trees and found that oxygen levels of 4 to 5 kPa inhibited root growth. Additionally, a study on almond trees done for the San Joaquin River Restoration Program (2015) indicates that, while oxygen concentrations over 10 kPa are optimal, root function is compromised at levels of 3 to 5 kPa. Of note, the effect of low oxygen conditions on plant health will depend on both the level and duration of low oxygen (SJRRP, 2015), plant growth state, plant adaptability, and the presence of pathogens (Costello, 1991).

The Present Study

In 2017, Sustainable Conservation worked with Bachand & Associates and several San Joaquin Valley growers and water districts to monitor and assess On-Farm Recharge (OFR) in order to meet the following goals:

- Evaluate compatibility of OFR with crops and farming practices;
- Collect information on the effects of soil saturation and oxygen levels; and
- Characterize agronomic response by almonds, grapes, pistachios, and walnuts.

This information is expected to increase knowledge about OFR compatibility with crops and farming considerations:

- OFR management practices and feasibility;
- Costs and benefits;
- Water resource benefits;
- Water availability and security;
- Groundwater management; and
- Strategies for farmers and GSAs to meet water needs

Two important components which Bachand & Associates focused on for this project were as follows:

1. Calculating and characterizing OFR direct recharge and infiltration rates, and
2. Assessing OFR implications to soil oxygen levels.

Surface water is used for OFR. For this study surface water was taken either directly from surplus river flow (flood flow) or from irrigation districts with surplus surface water. Surface water was applied to fields through flood systems.

This paper summarizes these efforts and presents the project results.

Methods

Water Applications

The study demonstrates OFR for *in lieu* and direct recharge. Water used for recharge was surface water, taken either directly from surplus river flow (flood flow) or from irrigation districts with surplus surface water allocations. In this study, surface water was applied on fields through flood systems. In this type of system, water enters subsections of the field (checks) created by berms and travels down the check as sheet flow. After one check is filled to the desired amount, water is diverted to another check. Groundwater applications were made using drip systems.

Direct recharge is water that infiltrates beyond the root zone towards groundwater. *In lieu* recharge is surface water that recharges the root zone and is used to meet crop evapotranspiration needs, thus reducing the need to pump groundwater. Often, one recharge event provides both direct and *in lieu* recharge.

Sites and Crops Tested

The study used seven sites to demonstrate OFR for direct and *in lieu* recharge. Five of the sites are in the Fresno area and the sixth is in Acampo, California, near Lodi. The seventh site is from a previous study (Bachand, 2017). Each site is composed of a pair of plots: one recharge and one control. The recharge plot received surface water for recharge; the paired control plot of similar soil type was not meant to receive recharge. These plots were sometimes separate fields and sometimes different parts of the same field. The plots are labeled with location IDs structured to identify anonymous grower, crop, and status as recharge (R) or control (C) plots (Table 1).

The crops tested included almonds (AL), pistachios (PS), walnuts (WL), and grapes (GR). All six sites were privately owned, commercial agricultural production sites, and were instrumented with moisture probes. Four plots were also instrumented with oxygen sensors. Oxygen sensors were put in both a recharge and control almond plot (TR-AL-R and TR-AL-C), a pistachio recharge plot (TR-PS-R), and a walnut recharge plot (DC-WL-R). Plots that could receive floodwater applications were also instrumented with pressure transducers to measure depth of standing water. Basic information about each plot is provided (Table 1). An additional previously monitored almond plot (AT-AL-R), in the Chowchilla area (Bachand, 2017), received recharge that was tracked in this.

Three plots (AC-GR-C, AT-GR-C, and EF-GR-C) were meant to be controls receiving only *in lieu* recharge but received direct recharge water, due to surface water application exceeding crop evapotranspiration. One plot, DC-WL-R, was meant to receive direct recharge but received in-lieu recharge only.

OFR DEMO SITE MONITORINIG AND ANALYSES

Table 1. Site and Instrumentation Summary

Crop	Site	Treatment	Plant Date	Cimis Station	Farm	Field	MP?[4]	T?[4]	MP and T Install Date	O2 Sensor[2] ?	NRCS Drainage
Wine Grapes	AC-GR-C[3]	Co	2003[1]	Manteca, #70	AC	TS	yes	yes	9/27/17	no	well drained
	AC-GR-R[3]	Rchg	2003[1]	Manteca, #70	AC	TS	yes	yes	9/27/17	no	somewhat excessively drained
Walnuts	DC-WL-C3	Co	2010	Fresno, #80	DC	DC	yes	yes	5/17/17	no	well drained
	DC-WL-R	Rchg	2010	Fresno, #80	DC	DC	yes	yes	5/17/17	yes	well drained
Raisin Grapes	EF-GR-C[3]	Co	2007	Parlier, #39	Ef	37	yes	yes	5/17/17	no	well drained
	EF-GR-R[3]	Rchg	2007	Parlier, #39	Ef	37	yes	yes	5/17/17	no	well drained
Almonds	TR-Al-C	Co	2013	Westlands, #105	TR	29-8	yes	no	5/16/17	yes	well drained
	TR-Al-R	Rchg	2013	Westlands, #105	TR	44	yes	yes	5/16/17	yes	well drained
Wine Grapes	TR-GR-C	Co	1993	Westlands, #105	TR	F-1	yes	no	5/16/17	no	somewhat poorly drained
	TR-GR-R	Rchg	1998	Westlands, #105	TR	27	yes	yes	5/16/17	no	somewhat poorly to well drained
Pistachios	TR-PS-C	Co	2006	Westlands, #105	TR	F-3	yes	no	5/16/17	no	somewhat poorly drained
	TR-PS-R	Rchg	2009	Westlands, #105	TR	19S	yes	yes	5/16/17	yes	somewhat poorly to well drained
Almonds	AT-AL-C[3]	Co	1976	Madera II, #188	AT	na	yes	no[5]	4/19/16	no	Somewhat poorly drained
	AT-AL-R[3]	Rchg	1976	Madera II, #188	AT	na	yes	no[5]	4/19/16	no	somewhat excessively drained

[1] Based on Google Earth: Southern end (south of instruments) planted between 3/14 and 3/15.

[2] All oxygen probes were installed 5/31/17 except at TR-PS-R, where they were installed on 6/28/17

[3] Both treatments in one field; [4] MP - moisture probe, T - transducer; [5] Transducers not operational in 2017

Instrument Installation

Soil Moisture Probe Installation

Sentek Drill & Drop TriSCAN 120 cm deep probes were installed on May 16 and May 17, 2017 by Irrigation Matters, a soil moisture monitoring company that is a distributor of Sentek products. The Sentek Drill & Drop TriSCAN probe is tapered. It was fitted into a hole drilled with a matching tapered auger to maximize direct contact with soil and minimize the potential for preferential path flow along probe sides. The probes measure volumetric water content (VWC), salinity as volumetric ion content (VIC), and temperature at 4-inch intervals, from 2 to 46 inches. The instruments were used to track water and constituent movement during recharge. Two instruments were installed at each location, each within the tree or vine row, to avoid damage. Each instrument was placed on the south or west side of the trees (depending on orchard orientation). Because the contractor was missing parts during installations, some instruments were not recording data for days after installation. This sort of issue underscores the importance of installing instruments well before recharge events might occur.

Surface Water Sensor Installation

Decagon CTD-10 sensors (vented pressure transducers) were also installed by Irrigation Matters to monitor water level, electrical conductivity, and temperature of surface water. The sensors were placed and secured within a 5-inch long, 4-inch diameter slotted PVC pipe placed vertically with the top edge flush with the ground. The purpose of the PVC pipes was to provide a protective structure to which the sensor could be attached. One sensor was installed at each location where surface water flow was expected, towards the edge of the tree row.

Oxygen Sensor Installation and Calibration

Bachand & Associates worked with Western Weather to install Apogee Oxygen sensors (model SO-110) to measure oxygen in the soil pore space (Table 1). Soil temperature is also output by the sensors.

Installation occurred on May 31, 2017 at DC-WL-R, DC-WL-C, TR-AL-R, and TR-AL-C (Fresno County). Because of recharge activities occurring at TR-PS-R, installation was delayed until June 28, 2017. The oxygen sensors were fitted with diffusion heads[1]. For each sensor, a 2.25-inch diameter hole was hand augered to the appropriate depth (10, 18, or 26 inches) and an oxygen sensor was positioned vertically at the bottom of the hole. Including the diffusion head, the instrument is 3.2 cm in diameter. Each hole was backfilled and compacted to prevent soil bridging that might lead to voids near the sensor. Bentonite plugs were placed every 6 inches to prevent preferential flow.

Oxygen sensors were calibrated in the lab by Western Weather. Oxygen sensors read in oxygen partial pressure. The oxygen probes measure the concentration of oxygen in soil as partial pressure of oxygen in soil air and report in units of kilopascal (kPa). Calibration occurred at standard temperature and pressure (25°C, 29.92 inches Hg). The calibration factor is derived by dividing ambient oxygen partial pressure (21.23 kPa at sea level assuming standard pressure at 101.325 kPa) by the measured voltage and estimating that 3.0 millivolts (mV) is equal to the mV reading when no oxygen is present. Oxygen sensor readings of zero indicate that the soil is saturated.

Water Applications and Recharge

Each grower tracked water applications using flow meters installed at the field level, and provided records of their water applications including start and stop dates and volume of water applied (

Table 2).

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[1] Diffusion heads are filters to protect the permeable Teflon membrane of the sensor, where gas diffusion occurs.

Table 2. Summary of Surface Water Applications

Site	Acre	Crop	Start Date	Stop Date	Recharge Volume (ac-ft)
AC-GR-R	13.7	Wine grape	10/12/17	10/24/17	136.5
AC-GR-C	9.1	Wine Grape	10/12/17	10/24/17	8.5
AT-Al-R	53.6	Almond	2/1/17	2/21/17	134.0
EF-GR-R	19.5	Raisin grape	10/25/17	11/6/17	31.9
EF-GR-C	18.5	Raisin grape	10/25/17	10/30/18	11.0
DC-WL-R	47.0	Walnut	6/9/17	6/15/17	17.2
DC-WL-R	47.0	Walnut	6/28/17	17/1/17	11.5
DC-WL-R	47.0	Walnut	7/14/16	7/16/16	17.6
DC-WL-R	47.0	Walnut	8/9/17	8/14/17	17.6
DC-WL-R	47.0	Walnut	8/29/17	9/2/17	20.5
DC-WL-R	47.0	Walnut	9/22/17	9/26/17	4.8
DC-WL-R	47.0	Walnut	10/19/17	10/24/17	18.6
TR-Al-R	76.0	Almond	4/2/17	4/15/17	53.0
TR-Al-R	76.0	Almond	5/28/17	6/17/17	98.8
TR-GR-R	77.5	Wine grape	3/30/18	4/22/17	96.8
TR-GR-R	77.5	Wine grape	5/7/18	6/27/17	15.9
TR-GR-R	77.5	Wine grape	7/9/17	7/10/17	0.9
TR-PS-R	35.0	Pistachio	3/26/18	4/15/17	67.1
TR-PS-R	35.0	Pistachio	5/7/17	5/13/17	32.6
TR-PS-R	35.0	Pistachio	5/27/17	6/3/17	36.3
TR-PS-R	35.0	Pistachio	6/11/17	6/17/17	27.2
TR-PS-R	35.0	Pistachio	7/2/17	7/3/17	8.1

Analyses

In Lieu Recharge

We assumed that recharge occurs only due to surface water applications. At some sites, drip with groundwater occurred during the same period as surface water applications. Water from these events is not included in recharge calculations because the applied water, extracted from groundwater, does not contribute to net groundwater recharge.

Surface water applications can provide *in lieu* and direct recharge. *In lieu* recharge occurs when surface water is used instead of groundwater to satisfy crop evapotranspiration (ETc). Direct recharge occurs when applied surface water flushes below the root zone towards groundwater. Rainfall, which occurred during the OFR events, was not included in tallies of direct or *in lieu* recharge because we are focused on the contribution of managed water application to recharge.

In Lieu Recharge. We defined *in lieu* recharge as follows:

In lieu recharge = $\sum ETc - \sum Prec + RZR$

Where,

$\sum ETc$ = Evapotranspiration for the specific crop and location, summed over event period
$\sum Prec$ = Precipitation, summed over the event period
RZR = Root zone replenishment, water applied to bring root zone to field capacity

With *in lieu* recharge maximum equal to the OFR application volume and minimum equal to zero.

For each OFR period, cumulative ETc was calculated between the end of the previous water application or precipitation event and the end of the surface water applications for recharge. This period was used so that we could assume soil was at or near field capacity at the start and end of the period and that water was not used to replenish the root zone. We calculated ETc based on the closest CIMIS station's reference evapotranspiration (ETo) data as follows:

$ETc = Kc * ETo$

Where,

Kc = The crop coefficient for the crop.

We used Kc values given by FAO (2012) for each crop. Kc values were customized for each field based on reported dates of important crop milestones such as bloom and harvest date.

Precipitation data was also collected from the closest CIMIS station. When rainfall amounts exceed ETc demands, it may move beyond the root zone to recharge groundwater. The contribution by rainfall in recharging groundwater was not included in the calculation of direct recharge because we are calculating recharge from the surface water application.

At two plots (AC-GR-R and AC-GR-C), no earlier rainfall or water application information was available, and so we estimated RZR, the water volume required to bring the root zone soil to field capacity, at the start of the OFR period. We estimated by subtracting the VWC immediately before water application from the field capacity at 4 in increments down to the 46-inch depth. The sum of the water required for each 4-inch soil thickness was taken as the total water required for RZR.

Direct Recharge. Using a water budget, we calculated direct recharge by subtracting *in lieu* recharge from water applied during the recharge event:

Direct Recharge = Water Applied - *In Lieu* Recharge

Where,

Water Applied = Total volume of water applied
In Lieu Recharge = Volume of water applied for *in lieu* recharge

Infiltration Rate Determination

The change in ponded water level was taken as the difference between the water level as it begins to drop and the water level at about 5 inches, the depth of the PVC housing for the transducer. We subtracted estimated evaporative water loss from water level change to determine the volume of infiltrated water. Dividing this number by the time required for the water level to drop provides infiltration rate.

At locations where pressure transducer data were not available, water level could not be used to determine infiltration rate. At AC-GR-R, shallow moisture probes indicated the constant presence of water during the recharge period. Therefore, infiltration rate was calculated as applied water, corrected for evaporation, divided by time period of maximum soil saturation (at 10 inches).

Field Capacity Determination

Field capacity (FC) is the soil moisture content at which excess water has drained and downward flow is negligible. Using a method described by Decagon (2017), FC was estimated from VWC trends by identifying the point when the temporal decline in VWC changes from a steep drop (due to water draining gravimetrically from soils) to a shallower decline (due to water being consumed through transpiration). To most accurately estimate FC, we analyzed moisture curves from relatively short water applications that started when the soil profile was relatively dry. This methodology reduces the possibility of conditions that might obscure FC, such as low permeability soil layers reducing water flow.

Calculation of Time Required for Water to Reach Below the Root Zone

We measured time required for water to extend below the root zone. We identified the time that water began infiltrating into the soil as the time when moisture first begins rising in an upper moisture sensor. We defined the depth of the root zone as the deepest moisture probe sensor (46 inches for all locations but AT-AL-R, where the probes are 48 inches deep). We assumed that water was moving beyond the root zone when the VWC at the deepest probe exceeded FC. Although roots may extend below 46 to 48 inches for some crops, roots are most dense in the upper area and so it is likely that water draining below that level is not significantly taken in by the plant.

Calculation of Percent Saturation and Volumetric Air Content

The moisture probes report water content as VWC, which can vary significantly, partly due to porosity differences by soil type. Measures that account for porosity include volumetric air content (VAC) and percent saturation:

1) VAC: Porosity minus VWC
2) Percent saturation: The percentage of pore space that is filled with water

Both measures require porosity estimates, estimated from FC and observed saturation values. We assumed that a subset of 10-inch deep soils was at or near saturation during prolonged floodwater applications and took the associated VWC measurements as observed porosities. Based on data from these sites, we calculated FC as 72% of observed saturation. Field capacity is reported to be approximately 50% of total porosity (Decagon). However, when soil becomes very wet, it reaches a critical porosity where air-filled pores are not interconnected, which stops air diffusion (Cook, 2013) but also likely limits further water saturation. When published values of critical porosities (which vary slightly by soil texture) were added to the observed porosities, physical porosity was found to equal half of FC.

We compared oxygen readings to measures of moisture (VWC, percent saturation, or VAC). Oxygen readings were taken at 10, 18, and 26-inch depths. Considering that oxygen readings are likely a result of oxygen uptake and diffusion in the surrounding soil, we averaged moisture measures to compare to oxygen readings. Thus, moisture measures for 18- and 26-inch depths were taken as the average value of results from the target depth and depths 4 inch above and below. For the 10-inch depth, 10 and 18-inch-deep results were averaged. The 6-inch depth was not included because this depth presents a different condition, often elevated within the tree-row berm. Averages were used to account for the heterogeneous nature of the soil profile.

Results and Discussion

The results and discussion cover OFR hydrology and chemistry (as related to salinity) and OFR implications on soil oxygen.

OFR Hydrology and Chemistry

Recharge Quantities

Eight monitoring plots received OFR in 2017 between February 1, 2017 and November 6, 2017 (Table 3). Surface water applications ranged from 0.6 to 10 ac-ft/ac, with direct recharge (defined as water that infiltrates beyond the root zone to groundwater) at these sites ranging from 0 to 9.4 ac-ft/ac (0 to 113 inches). Surface water applied but used for ET (*in lieu* recharge) ranged from 0 to 2.3 ac-ft/ac (0 to 27.5 inches). *In lieu* recharge volumes reduce groundwater pumping because groundwater is not being used to meet crop evapotranspiration needs.

Table 3. Recharge at 2017 Demonstration Sites

Site[5]	Acre	Crop	Water Application[1]		Applied Water Vol (ac-ft)	Applied Water (Ac-ft/ac)	Applied Water (in)[6]	Etc[2] (in)	Prec[2] (in)	In Lieu[3] Recharge (in)	Direct[4] Recharge (in)
			Start	End							
AC-GR-R	13.7	Wine grape	10/12	10/24	136.5	10.0	119.6	0.7	0.1	6.6	113.0
AC-GR-C	9.1	Wine grape	10/12	10/24	8.5	0.9	11.2	0.7	0.1	6.6	4.6
AT-Al-R/C	53.6	Almond	2/1	2/21	134.0	2.5	30.0	1.2	1.9	0.0	30.0
DC-WL-R/C	47.0	Walnut	6/9	10/24	107.9	2.3	27.5	35.8	0.3	27.5	0.0
EF-GR-R	19.5	Raisin grape	10/25	11/6	31.9	1.6	19.7	3.6	0.2	3.5	16.2
EF-GR-C	18.5	Raisin grape	10/25	10/30	11.0	0.6	7.1	3.4	0.2	3.2	3.9
TR-Al-R	76.0	Almond	4/2	6/17	151.7	2.0	24.0	14.8	2.2	12.5	11.4
TR-GR-R	77.5	Wine grape	3/30	7/10	113.6	1.5	17.6	14.9	2.2	12.7	4.9
TR-PS-R	35.0	Pistachio	3/26	7/3	171.2	4.9	58.7	18.8	2.2	16.5	42.2

[1] Water application may refer to either a single event or a series of water application events. All occurred in 2017.

[2] ETc (evapotranspiration) and Precip (precipitation) were calculated by summing daily values between end of previous irrigation or precipitation event and end of OFR water application, as defined by drop in VWC values to Fc. The exception was Ac-Gr-R/C, where no data were available on previous irrigation timing so ET start date was taken as start of water application. Because soil at Ac-Gr-R/C was below field capacity at start , we estimated the water volume required for root zone replenishment (RZR) to field capacity. RZR was calculated at 6 inches based on VWC data.

[3] In Lieu recharge was calculated as Etc - Precipitation- Refill Root Zone. The Refill term was calculated only for AC-Gr-C/R (see note 2). Maximum In Lieu recharge is total recharge volume and minimum is 0.

[4] Direct Recharge = Water Applied- In Lieu Reecharge

5Miiddle two letters refer to crop type (GR- grape; AL - Almond; WL - Walnut; PS - Pistachio. Last letter designates site as recharge(R) or control (C) site

[6] Applied water in inches is calculated from normalized volume (ac-ft)/ac = ft. Inches = ft * 12 in/ft

Infiltration Rates and Transport Time Through the Root Zone

Infiltration rate estimates are shown on Table 4. Infiltration rates were not calculated when drip applications occurred during a drawdown period between recharge events. The mean infiltration rates ranged from 2 to 7 inches/day. It is worth noting that TR-PS-R, located in an area mapped as "somewhat poorly drained" by the NRCS, had a rate of 3.5 inches/day, which is higher than infiltration rates measured at some "well-drained" sites. At DC-WL-R, infiltration rates appeared to drop over time, from 3.4 inches/day in June to 1.0 inches/day in October. This was not observed at the other plots at TR, but this phenomenon was also observed at a previous recharge demonstration project at TR (Bachand, 2017).

Water infiltrating from the surface enters the soil profile and fills pores to FC before moving deeper. We measured time required for water to extend below the level of the deepest probe (46 inches for all but

AT-AL-R, where the probe is 48 inches deep). Time to travel below the root zone ranged from 0.5 to 24 hours from the start of water application (Table 4).

Table 4. Infiltration Rates and travel time through the root zone

Site	**Crop**	**NRCS drainage description**	**Date Range**	**Surface Water Infiltration Rate (in/day)**	**Mean Surface Water Infiltration Rate (in/day)**	**Time for water to travel to 46" (hours)[4]**
AC-GR-R	Wine grapes	Somewhat excessively drained	10/12-11/1	6-8	7	9.5-14.5
AT-Al-R	Almonds	Well drained to somewhat excessively drained	NA		NA	0.5-10
EF-GR-R	Raisin grape	Well-drained	NA		NA	NA[1]
DC-WL-R	Walnuts	Well-drained	6/12-6/13	3.4	2.0	NA[2]
			8/12-8/14	2.0		
			9/1-9/4	1.6		
			10/23-10/25	1.0		
TR-PS-R	Pistachios	Somewhat poorly drained	6/1-6/4	3.8	3.5	12-24
			6/14-6/17	3.1		
			7/5-7/6	3.6		
TR-Al-R	Almonds	Well-drained	NA		NA	NA[3]
TR-GR-R	Grapes	Well-drained	5/29-5/31	2.2	2.2	12
			6/28-6/30	2.2		

Notes:

[1] Recharge period not well defined so difficult to calculate travel time.

[2] Fc may not have been reached at this field

[3] Drip irrigation occurred along with surface water irrigation and made quantifying travel time difficult

[4] Defined as elapsed time between soil reaching field capacity at 46" and 1st indication of water at any depth (within

Effect of Recharge on Salinity

The Sentek moisture probes measure salinity as VIC, a measurement dependent on both VWC and soil type (Sentek, 2003). VIC before and after surface water applications were compared for two plots, DC-WL-R and EF-GR-R (Table 5). Direct recharge achieved on the two fields using floodwater applications was 0 inches and 16.2 inches respectively. We observed VIC decreases in shallow 10 inch and 18-inch soil averaging about 6% for both sites. Deeper soil depths at DC-WL-R showed an increase in VIC, indicating that salts may have been flushed from the shallow to deeper soil, possibly because there was not enough water applied to flush salts from the deeper root zone; this is consistent with the calculation of no direct recharge at DC-WL-R. For EF-GR-R, which had 16.2 inches of recharge, VIC decreased 2% in soils from 26 to 42 inches deep. The observed reduction in salt content is less than we would have expected based on measured TDS in pore water from previous soil sampling and analyses at other recharge plots. It is possible that the VIC measurements are not adequately representing pore water salinity.

VIC removal was also investigated by comparing data from four different paired sites (AC-GR, TR-AL, TR-GR, TR-PS) with apparently similar soil, as defined by both texture (when available) and estimated FC (Table 6). This less reliable comparison indicated VIC drops on average 2.7%. We observed VIC reductions of 11% and 9% for plots with 115 inches and 11 inches of recharge, respectively (AC-GR and TR-AL). However, we observed increases in VIC at two sites with recharge of 5 inches to 42 inches (TR-GR and TR-PS). We did not observe a consistent pattern of VIC change with depth in the data.

Table 5. VIC reduction in plots where data is available both before and after surface water application

Site	Crop	Depth (in)	Moisture Probe	Pre-Water VIC[1]	Post-Water VIC[1]	VIC Drop[2]	Avg VIC Drop for Depth	Avg VIC Drop for Shallow & Deeper Soil	Avg VIC Drop for Field	Applied Water[3] (in)	Re-charge[3] (in)
DC-WL-R/C	Walnuts	10	DC-WL-C-E	1344	1408	-4.8%	2.8%	6.3%	2.0%	27.5	0
			DC-WL-R-E	1315	1247	5.1%					
			DC-WL-R-W	1387	1273	8.2%					
		18	DC-WL-C-E	1678	1480	11.8%	9.8%				
			DC-WL-C-W	1377	1333	3.2%					
			DC-WL-R-E	1544	1372	11.2%					
			DC-WL-R-W	1507	1309	13.1%					
		26	DC-WL-C-E	1455	1571	-8.0%	-3.3%	-0.9%			
			DC-WL-C-W	1234	1289	-4.4%					
			DC-WL-R-E	1382	1347	2.5%					
		34	DC-WL-R-E	1430	1378	3.6%	2.1%				
			DC-WL-R-W	1346	1337	0.6%					
		42	DC-WL-R-E	1322	1343	-1.6%	-1.6%				
EF-GR-R	Raisin Grapes	10	EF-GR-R-E	1322	1243	6.0%	5.1%	5.8%	3.7%	19.7	16.2
			EF-GR-R-W	1230	1178	4.3%					
		18	EF-GR-R-E	1255	1171	6.7%	6.5%				
			EF-GR-R-W	1238	1161	6.2%					
		26	EF-GR-R-E	1317	1298	1.5%	2.9%	2.2%			
			EF-GR-R-W	1173	1122	4.3%					
		34	EF-GR-R-E	1367	1363	0.3%	1.9%				
			EF-GR-R-W	1422	1374	3.4%					
		42	EF-GR-R-E	1344	1336	0.6%	1.9%				
			EF-GR-R-W	1385	1341	3.2%					

Notes:

[1] Volumetric Ion Content (VIC) measurements depend on VWC and soil type. VIC measurements taken for the same VWC range +/- 0.25%) for each location. VIC measurements taken a maximum of 21 days before and after water application period.

[2] Drop in VIC calculated as (Control VIC - Recharge VIC)/Control VIC

[3] See Table 3

Table 6. VIC drops for paired recharge and control plots

Field Set[1]	Crop	Depth (in)	VIC measurements[2] Recharge[3]	Control	VIC Drop[4] (%)	Avg VIC Drop for Shallow & Deeper Soil (%)	Average VIC Drop for Field Set (%)	Irrig Water (in)[5]	Recharge (in)[5]
AC-GR	Grapes	10	1110	1142	2.8	2.8	11.4	119.6	114.5
		30	1048	1310	20.0	20.0			
TR-AL	Almonds	10	1379	1496	7.9	12.2	8.9	24.0	11.4
		18	1321	1582	16.5				
		26	1353	1499	9.7	5.6			
		34	1450	1471	1.4				
TR-GR	Grapes	10	1426	1388	-2.7	-5.1	-3.8	17.6	4.9
		18	1392	1296	-7.4				
		26	1421	1413	-0.6	-2.9			
		34	1407	1408	0.1				
		42	1318	1218	-8.2				
TR-PS	Pistachios	10	1394	1394	0.0	0.0	-5.6	58.7	42.2
		18	1436	1180	-21.7	-8.4			
		26	1395	1469	5.0				
							Average for sites	2.7	

Notes:

[1] Field Set includes field or area under Recharge and Control treatments

[2] Volumetric Ion Content (VIC) measurements depend on volumetric water content (VWC) and soil type. VIC measurements taken for the same VWC range +/- 0.25%) for each recharge/control pair. When soil type is known, pairs include soil with similar soil type only. VIC measurements taken within 21 days of last recharge event.

[3] At three recharge sites, two sets of VIC measurements were available and are averaged here. The site locations and individual measurements are 10" TR-GR (1426, 1426); 10" TR-PS (1405,1384); 18" TR-PS (1436,1395)

[4] Drop in VIC calculated as (Control VIC - Recharge VIC)/Control VIC

[5] See Table 3

OFR Implications on Soil Oxygen

Although there are many uncertainties in defining a problematic level and duration of low oxygen levels, we used levels of 10 kPa and 5 kPa as benchmarks of potential suboptimal and detrimental conditions, respectively. These benchmarks were used to compare the effects of different water applications to oxygen conditions within the soil.

Typical Soil Oxygen Responses to Flooding and the Definition of Terms

Figure 1 shows oxygen and saturation change over time during recharge events (using flood systems) and drip applications. Both graphs show data from soil 10 inches deep. For both situations, oxygen tends to decrease when percent saturation increases. However, drip application events push oxygen levels below 10 kPa less often than flood applications and do not push oxygen levels below 5 kPa, as occurs with the flood applications.

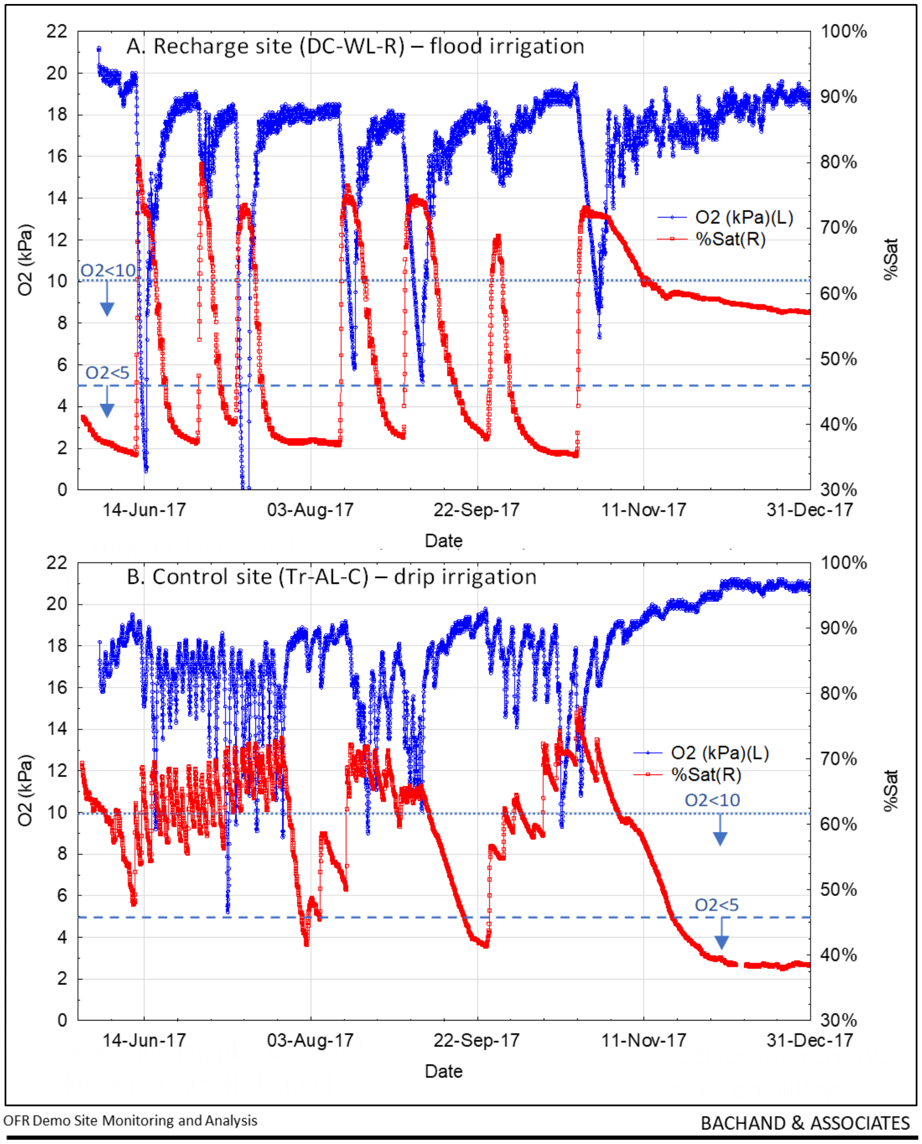

Figure 1. Oxygen and percent saturation over time for recharge and control plots (10-inch depth). A. The water application events were for in lieu recharge through flood applications. For each water application, saturation in soil increased and oxygen levels dropped. B. Oxygen levels related to drip applications did not drop below 5 kPa.

Figure 2 focuses on one recharge event to better observe changes in soil moisture and oxygen and to define terms. After the flood application begins, soil saturation increases and the oxygen level drops. The oxygen drop ends when the oxygen level reaches a minimum level, subsequently leveling out. The rate of oxygen decline or depletion is quite constant and is referred to here as "oxygen depletion rate." The period when oxygen stabilizes and increases is termed "oxygen recovery." In this example and in most instances, oxygen begins to stabilize when saturation is still relatively high but has begun to decline. We determined the start and end of each flood application by reviewing pressure transducer data and, if not available, shallow soil moisture probe data. The start of application was defined as either first standing water or first increase in soil moisture. The end of the flood application was defined as end of standing water or first decrease in shallow soil moisture. In this example from sensors at the 10-inch soil depth, oxygen drop ends approximately at the time application ends. This relationship is not always the case, especially in deeper soil.

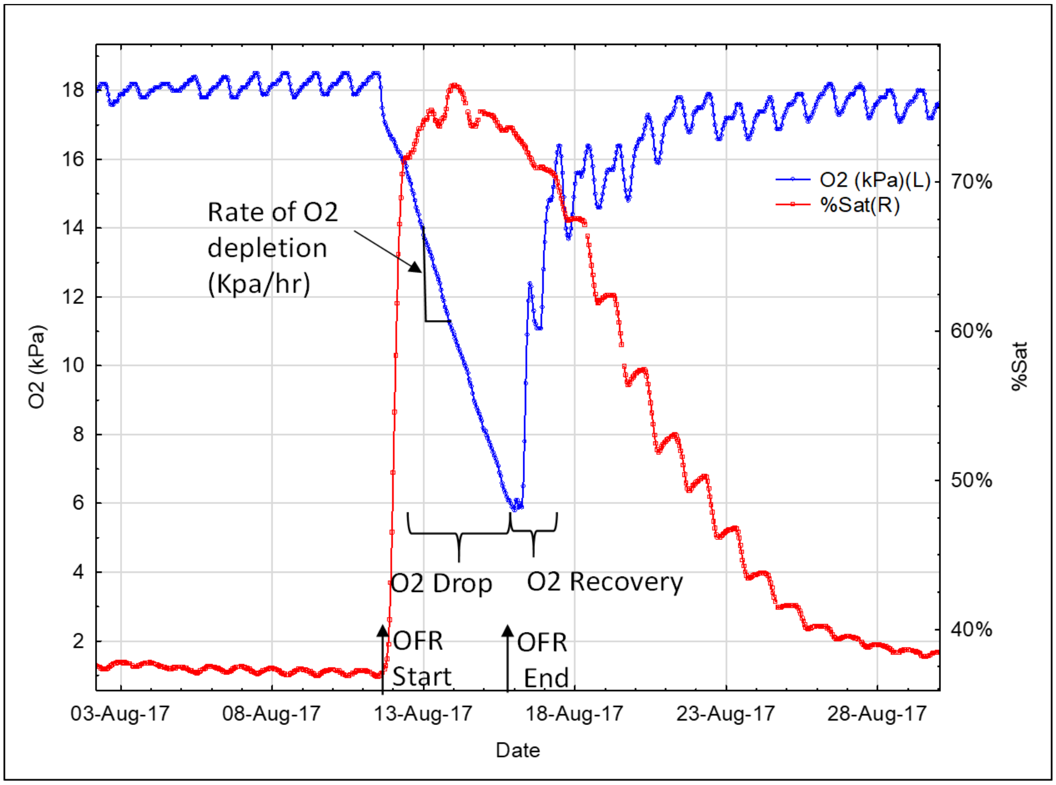

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Figure 2. Oxygen and percent *saturation over time for one water application at plot DC-WL-R, 10 in depth. Oxygen drops at steady rate after water application begins and soil moisture content increases.*

Soil Oxygen Levels During Drip and Floodwater Applications

Data from two sets of paired oxygen and moisture probes associated with 10, 18, and 26-inch soil depths were analyzed over 18 water application events, totaling 108 potential depth and location specific wet-dry cycles for each event (2 pairs x 3 depths x 18 events). After filtering the data for quality, we identified 94 cycles suitable for analyses. Information associated with these cycles is shown in Table 7 for recharge and in Table 8 for drip applications. These tables show averages of two sets of data, when available.

We compared oxygen levels with benchmarks of 5 kPa or 10kPa. In six of nine recharge events, oxygen dropped below 10 kPa in 10- and 18-inch soil depths. Levels also reached below 5 kPa, mostly at the 10-inch depths. For one direct recharge event, oxygen dropped below 5 kPa in all three monitored depths. Oxygen did not drop below 5 kPa during any of the drip application events. In seven of nine drip applications, oxygen dropped below 10 kPa at the 10-inch depth. Oxygen did not drop below 10 kPa within deeper soils during these drip applications.

Table 7. OFR wet-dry cycle information

Site[2]	Date	Type [1]	Irrig Length (days)	Max SW Depth (ft)	Sensor Depth (in)	Min O2 kPa	Max % Sat	Days of O2 Drop	Days - O2 Recovery	Hours - O2<10 kPa	Hours - O2<5 kPa
DC-WL-R	6/11	I	2.4	0.9	10	0.0	89%	2.2	6.4	64.5	47
					18	11.5	90%	2.7	7.3	4.5	0
					26	13.6	84%	3.8	7.4	0	0
DC-WL-R	6/30	I	2.3	0.5	10	14.5	87%	1.9	2.8	0	0
					18	15.7	87%	2.0	5.9	0	0
					26	15.7	60%	4.2	5.6	0	0
DC-WL-R	7/11	I	3.3	0.7	10	1.7	85%	2.9	4.0	60	36
					18	8.7	87%	3.0	3.9	25	0
					26	13.3	69%	3.8	7.2	0	0
DC-WL-R	8/11	I	4.0	0.9	10	2.7	85%	4.0	1.3	57.5	21.5
					18	7.8	85%	3.8	3.9	30	0
					26	12.0	87%	4.6	5.0	0	0
DC-WL-R	8/30	I	5.8	0.9	10	2.1	49%	4.8	2.9	95.5	39.5
					18	5.7	86%	5.1	3.6	83	17.5
					26	10.4	72%	5.3	4.2	6	0
DC-WL-R	9/24	I	2.8	0.6	10	15.6	54%	1.7	5.8	0	0
					18	16.1	74%	2.3	6.0	0	0
					26	15.4	79%	2.3	6.2	0	0
DC-WL-R	10/21	I	9.1	0.9	10	5.5	79%	6.5	2.9	64	16.5
					18	10.4	48%	6.9	2.4	6	0
					26	12.9	77%	6.7	2.4	0	0
TR-AL-R	6/2	I&D	4.1	na	18	13.1	73%	4.2	1.3	0	0
					26	12.2	72%	4.0	5.7	0	0
TR-PS-R	7/1	I&D	5.5	1.1	10	2.7	79%	4.6	2.7	83.5	52
					18	4.8	84%	5.9	6.4	55	2
					26	3.8	78%	5.6	8.4	90	15

[1] Direct Recharge (D); In-lieu Recharge (I)

[2] Miiddle two letters refer to crop type (GR- grape; AL - Almond; WL - Walnut; PS - Pistachio).

Table 8. Drip application wet-dry cycle information

Site	Date	Irrig Length (days)	Depth (in)	Min O2 kPa	Max % Sat	Days of O2 Drop	Days of O2 Recovery	Hours - O2<10 kPa	Hours - O2<5 kPa
TR-AL-C	6/15	1.3	10	11.0	68%	1.2	0.6	4	0
			18	16.8	64%	1.2	0.8	0	0
			26	17.2	51%	1.1	0.6	0	0
TR-AL-C	7/7	1.5	10	5.2	71%	0.8	0.9	22	0
			18	16.6	69%	0.9	1.0	0	0
			26	17.2	63%	0.9	1.0	0	0
TR-AL-C	7/10	0.6	10	9.4	70%	0.3	0.9	3	0
			18	16.5	70%	1.0	0.8	0	0
			26	17.0	65%	0.8	0.3	0	0
TR-AL-C	7/16	0.9	10	9.1	71%	0.5	1.0	9	0
			18	16.2	71%	0.4	1.1	0	0
			26	17.0	69%	0.0	1.8	0	0
TR-AL-C	7/24	0.8	10	8.8	73%	0.4	0.5	5	0
			18	na	na	0.5	3.4	na	na
			26	16.8	74%	0.0	5.4	0	0
TR-AL-C	8/18	1.5	10	9.9	67%	1.3	1.0	4.5	0
			18	15.0	75%	1.3	1.1	0	0
			26	16.0	81%	0.9	1.1	0	0
TR-AL-C	10/15	1.3	10	8.8	68%	0.7	3.5	23.5	0
			18	15.2	68%	1.8	15.0	0	0
			26	16.0	66%	2.5	14.9	0	0
TR-AL-R	6/19	0.6	10	13.4	69%	1.2	0.7	0	0
			18	14.0	67%	1.7	1.2	0	0
			26	13.6	68%	2.0	0.8	0	0
TR-PS-R	8/18	0.8	10	12.5	79%	1.2	0.6	0	0
			18	15.6	83%	1.6	7.9	0	0
			26	14.7	79%	1.1	4.3	0	0

Oxygen Measurements During Summer Recharge Events

Figure 3 demonstrates how oxygen changes with time after the start of summer (June-August) recharge events. Each line of points shows the drop in oxygen with time and illustrates the importance of water application duration. The slope of each line is the rate of change of oxygen depletion. Rates of oxygen depletion vary significantly, even within the summer and for a given location and depth, so that the final oxygen levels also vary considerably for a given elapsed time after the start of application.

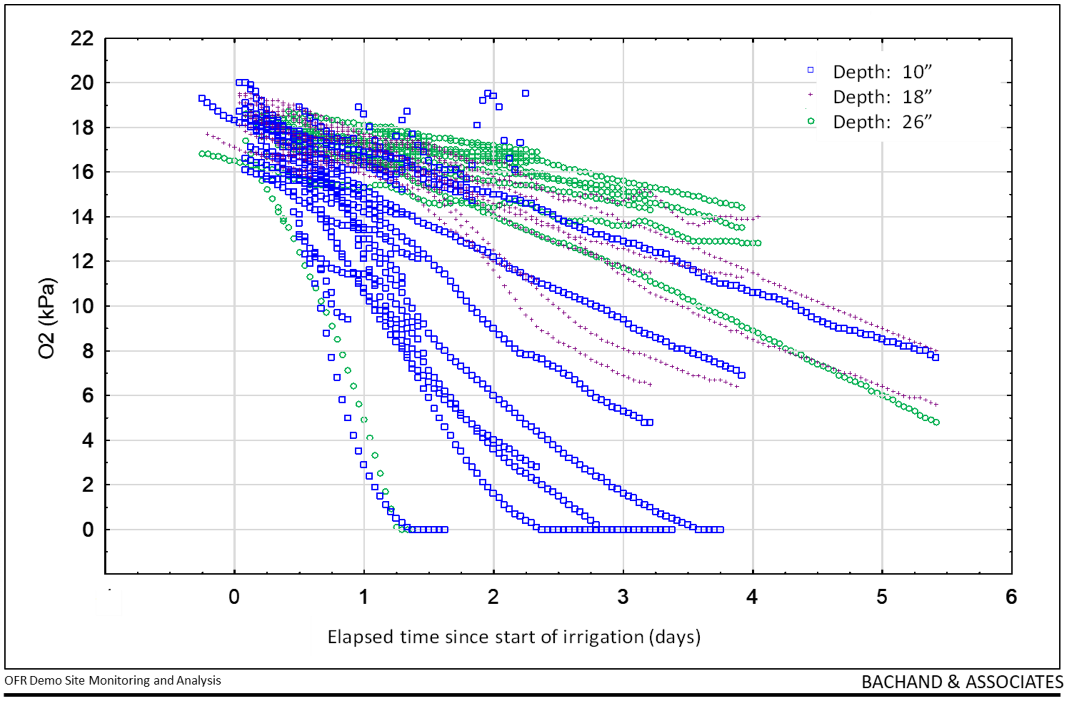

Figure 3. Oxygen with elapsed time after water application (summer only). The slope of oxygen depletion rates varies, even within the same soil depth.

Oxygen Depletion Dependency on Soil Depth and Season

Rates of oxygen depletion (kPa/hr) by season (summer and fall) and by depth are shown in Figure 4. Depletion rates tend to be greater (larger negative values) for shallow soil relative to deeper soil and tend to be greater in summer versus fall. The greater rates observed at the 10-inch depth may be due to closer proximity to the oxygen barrier created by floodwater and/or be due to greater density of respiring plant roots and/or soil microbes. The greater difference by soil depth observed in summer (a period of greater respiration rates) relative to fall (lower respiration rates) seems to indicate respiration is responsible. Mean rates are about half as great for 18 and 26 inches as for 10 inches in the summer. Both plant and soil microbe respiration are likely higher during the summer.

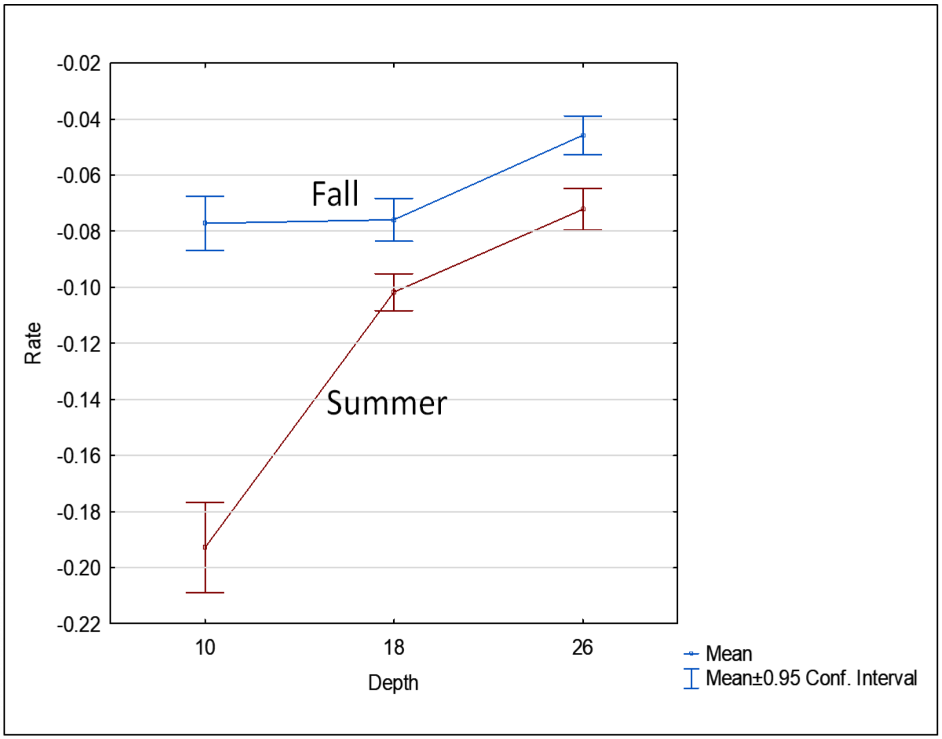

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Figure 4. Oxygen depletion rates with depth and season (rate oxygen change kPa/hr). Oxygen depletion rates are higher (more negative) in summer than in fall.

Oxygen Measurements with Soil Saturation

Figure 5 displays oxygen as a function of percent saturation for both drip and floodwater applications, including recharge events. From this graph, we see that oxygen levels below about 10 kPa are generally associated with percent saturation levels of more than 74%. The graph illustrates the variability in the data, with oxygen sometimes dropping at 80% and sometimes at 90% saturation. Although not evident from the graphs, for a given soil (site and depth), oxygen drops at different saturations for different cycles. This indicates that oxygen is not dropping in response to a “critical” level of VWC but that other factors are involved. We used a correlation analysis to discern factors responsible for this variation.

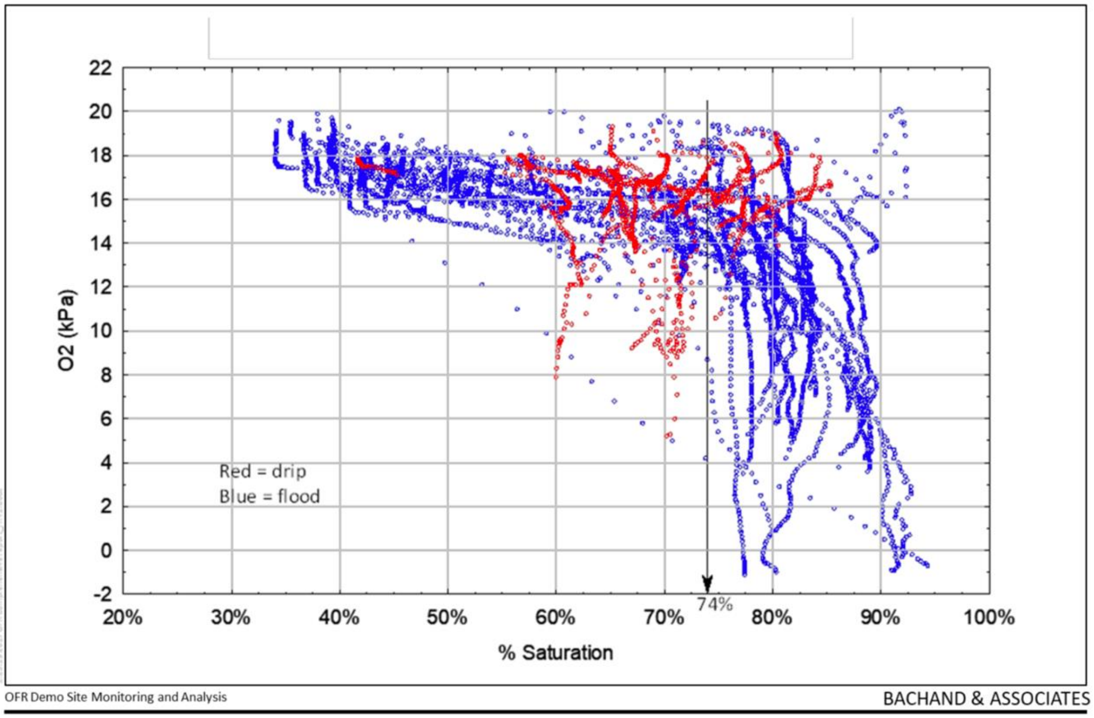


Figure 5. Oxygen as a function of percent *saturation (flood and drip water applications). Oxygen levels tended to drop when soil was more than 74% saturated.*

Relationships with and Drivers of Soil Oxygen Levels

We reviewed many variables possibly linked to oxygen depletion in soil: percent saturation, initial oxygen, oxygen depletion rates, volumetric air and water content, soil temperature, soil texture, and water application variables. We also analyzed the relationship between elapsed time above 74% saturation where, based on our data (Figure 5), oxygen levels tend to drop. The drop indicates that oxygen diffusion rates begin to drop below respiration rates, leading to oxygen depletion dependency on time.

Soil texture and soil temperature did not correlate well to oxygen levels. It is likely that correlation would have been observed if the plots had greater textural differences and if observations were made over wider temperature ranges. Soil texture and structure (structure was not evaluated in this study) greatly affect the ability of water and air to move through soil (Noah, 2018). In the case of temperature, both root and soil microbe respiration (and thus oxygen uptake) reportedly increase with temperature (Peng, 2009).

VWC and VAC also did not correlate well with oxygen levels, even though these measures are known to be important to oxygen diffusion. VWC and VAC are dependent on soil porosity (for instance, a clay loam at field capacity will have a much higher VWC than a sand at field capacity). Percent saturation, which is VWC standardized to porosity, did correlate with oxygen depletion.

Table 9 shows the results of the correlation analyses for factors with the most significant relationships with either minimum oxygen (per cycle) or with oxygen measures with time (elapsed time of soil at or over 74% saturation). Highlighted cells designate variables that have a significant negative correlation of more than 0.6 ($p < 0.05$). Water application related variables (maximum surface water depth and irrigation duration) were found to inversely correlate with minimum oxygen for most depths and seasons. Additionally, oxygen depletion rate and elapsed time negatively correlated with oxygen levels during the summer. Increased saturation also correlated with lower oxygen in some instances, particularly in winter.

The correlations point to physical processes that could lead to low oxygen levels. Surface water depth may correlate with oxygen levels because even if shallow surface water doesn't completely cover the soil surface, the surface water is a barrier to oxygen diffusion from the air. The longer the irrigation, the longer the barrier is present to prevent oxygen diffusion. Negative correlations of oxygen levels to percent saturation measures occur because, with more water-filled soil pores, there are less air-filled pores for oxygen diffusion. The longer soil is at or above a saturation condition that could limit oxygen diffusion (taken here as 74% saturation), the more time available for oxygen levels to drop. Similarly, the greater the oxygen depletion rate, the faster oxygen levels will drop. The oxygen depletion rate is a gauge of the degree in which oxygen diffusion can satisfy the oxygen uptake (i.e. respiration).

Table 9. Correlation coefficients (r's) for selected variables with oxygen levels after surface water applications. Red indicates significant correlation, $p<.05$; these correlations are highlighted where $r>0.60$.

Depth	Season[1]	Number of cycles	Minimum O2 level reached after irrigation				O2 Measure (time=t)	
			Irrig Duration (days)	Max %Sat	O2 Depletion Rate (kPa/hr)	Max Surface water depth	Elapsed hours, %Sat> 74% (time=t)	%Sat Measure (time=t)
10	Summer	12	-0.34	0.13	-0.64	-0.64	-0.21	-0.15
18	Summer	12	-0.79	-0.71	-0.69	-0.77	-0.60	-0.40
26	Summer	11	-0.75	-0.48	-0.92	-0.85	-0.95	-0.19
10	Fall[2]	4	-0.97	-0.77	0.38	-0.97	-0.57	-0.69
18	Fall[2]	4	-0.97	-0.99	0.47	-0.97	-0.31	-0.73
26	Fall[2]	4	-0.97	-0.92	0.26	-0.97	-0.50	-0.28

[1] Summer defined as June, July, August. Fall defined as September, October, November.

[2] Correlation coefficients for fall are based on small sample size and may change considerably when more data are available.

We further analyzed data for trends related to oxygen depletion rates because the reason for the different rates is not apparent; oxygen depletion rates are sometimes different for the same site during the same time of year. An example is shown in Figure 6, which shows a site (DC-WL-R-East) under different water applications: Figure 6A1-2 and 6B1-2 show oxygen response to increasing moisture during a water application starting on August 11, 2017 and June 11, 2017, respectively. Percent saturation started below 40% and ended at 82% to 85% for both cases. Additionally, they both experienced the same maximum water level, although the August 11, 2017 application was longer than the June 11, 2017 application (Figure 5). However, during the August 11, 2017 water application (Figure 6A1), the rate of oxygen depletion is constant while moisture increases and in the June 11, 2017 water application (Figure 6B1), the rate of oxygen depletion increases with increasing moisture. The resulting minimum oxygen is 6 kPa for the August 11, 2017 water application (Figure 6A2) and 1 kPa for the June 11, 2017 water application (Figure 6B2). We observed that, for all wet-dry cycles in 10" soil, oxygen dropped below 5 kPa only when the oxygen depletion rate increased with percent saturation.

A difference between graphs 6A1 and 6B1 is the rate of change in moisture (saturation). To check if the rate of moisture rise is related to the rate of oxygen depletion, we compared the rate of increase of different moisture measurements to minimum oxygen for all cases. We found the best correlation is with VWC rise rate (or VAC drop rate). VWC rise rate is the same as VAC drop rate because the porosity term cancels out:

$$(\text{Porosity} - \text{VWC}_t) - (\text{Porosity} - \text{VWC}_{t-1}) = \text{VWC}_{t-1} - \text{VWC}_t$$

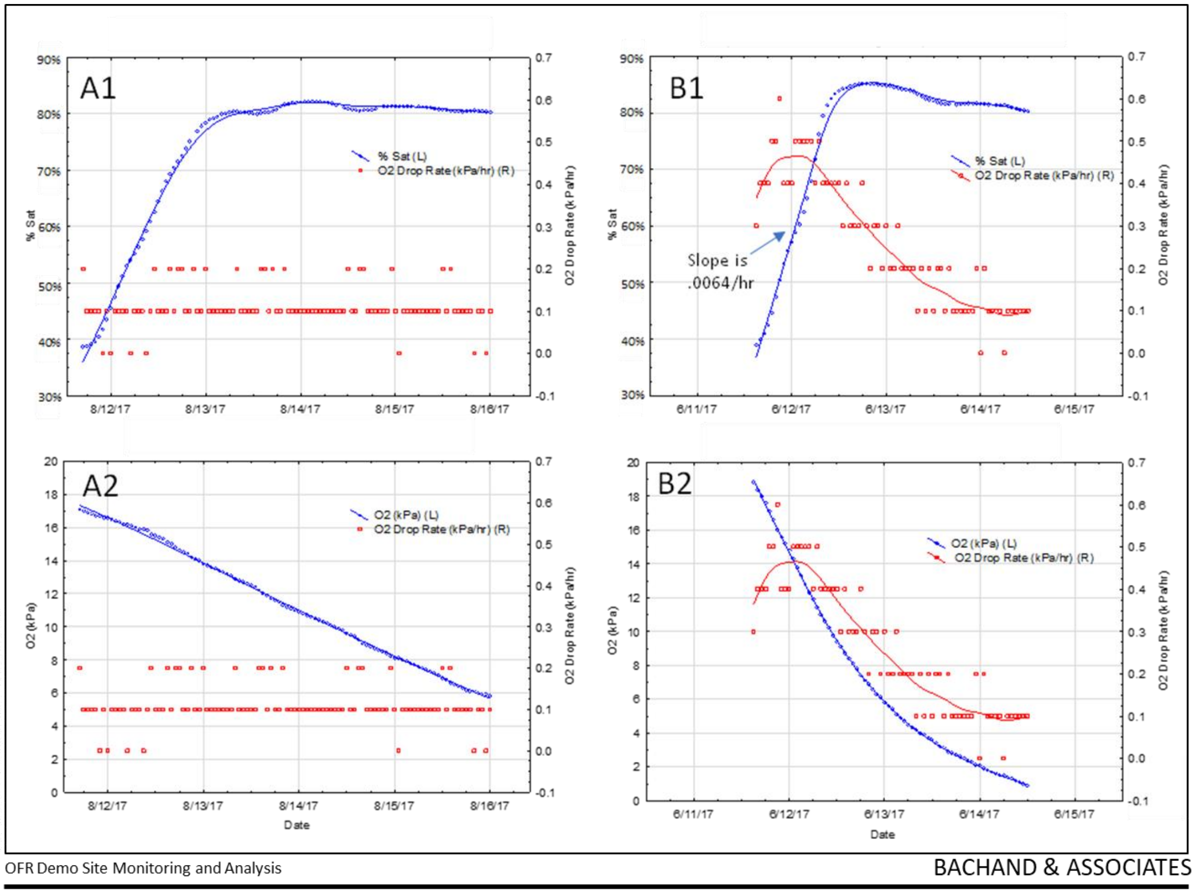


Figure 6. Oxygen depletion rates with (1) percent saturation and the resulting (2) oxygen levels at DC-WL-R East, with A water application starting 8/11/17 and B water application starting 6/11/17.

The correlation between minimum oxygen and VWC rise rate for all cases is r = -0.6 ($p < .05$) (Figure 8a). High VWC rise rates indicate a situation where water is rapidly filling soil pores and may signify a condition in which oxygen diffusion into soil is difficult.

Do Soil Oxygen Levels Under Direct Recharge Differ from Levels for Flood and Drip Applications to Meet Crop Needs?

Importantly, in considering water management, Table 10 provides some additional context, comparing oxygen metrics under direct recharge, *in lieu* recharge, and drip application to meet crop needs. Data shown includes: minimum oxygen, oxygen recovery time, maximum percent saturation, and number of hours soil remained at oxygen levels of 5 and 10 kPa. Table 10 shows averages of the two sets of data per pair of plots, when available. Maximum percent saturation, oxygen drop, and oxygen recovery times during direct recharge fell within ranges found for *in lieu* recharge.

Oxygen levels in shallow and mid depth soils tended to be lower under direct recharge than other water applications. Deeper soils under direct recharge experienced longer durations between 5 to 10 kPa, though that was not found for shallower and mid depth soil. It is important to note that data for direct recharge events (n = 2) were more limited than for other types of water application events (n = 16). However, if water applications for direct recharge are similar to flood irrigation for crop needs, oxygen levels may be less likely to drop to a level that could constitute a threat to crop health.

Table 10. Summary of oxygen and saturation ranges for drip and floodwater applications for irrigation or recharge.

Type of Water Application	Duration of Water Applications (days)	# monitored events	Depth (in)	Min O2 (kPa)	Max % Sat	Days of O2 Drop	Days of O2 Recovery	Hours - O2<10 kPa	Hours - O2<5 kPa
Drip Irrigation	0.6-1.5	9	10	5.2 - 13.4	67% - 79%	0.3 - 1.3	0.5 - 3.5	0 - 24	0
			18	14.0 - 16.8	64% - 83%	0.4 - 1.8	0.8 - 15	0	0
			26	13.6 - 17.2	51% - 81%	0.0 - 2.5	0.3 - 15	0	0
In-Lieu Recharge (Flood)	2.3-9.1	7	10	0.0 - 15.6	60% - 90%	1.7 - 6.5	1.4 - 6.5	0 - 96	0 - 47
			18	5.7 - 16.1	49% - 87%	2.0 - 6.9	2.4 - 7.3	0 - 83	0 - 17
			26	10.4 - 15.7	48% - 79%	2.3 - 6.7	2.4 - 7.4	0 - 6	0
Direct Recharge (Flood)	4.1-5.1	2	10*	2.7	79%	4.3	3.0	84	52
			18	4.8 - 13.1	73% - 84%	4.2 - 5.9	1.3 - 6.4	0 - 55	0 - 2
			26	3.8 - 12.2	72% - 78%	4.0 - 5.6	5.7 - 8.4	0 - 90	0 - 15

* Only one monitored event was available at this depth

Hypothesis: A Conceptual Model of Oxygen Drivers

From the correlations and observations, we present a conceptual model of drivers of soil oxygen levels, consumption, and transport. Plant and microbe respiration consume soil oxygen levels. Where and when depends upon root distribution and time of year. Oxygen is replenished through diffusive transport of oxygen from the surface to soil pores across and at depth in the root zone. Several factors can limit that diffusive transport. Surface water can provide a surface barrier preventing surface diffusion of oxygen into the soil profile. Pore volume moisture can form barriers to pore connectivity and oxygen diffusion across those pore spaces, limiting replenishment pathways and rates. Reduced oxygen in the pore space provides feedback to the plant, reducing “local” respiration rates by the plant.

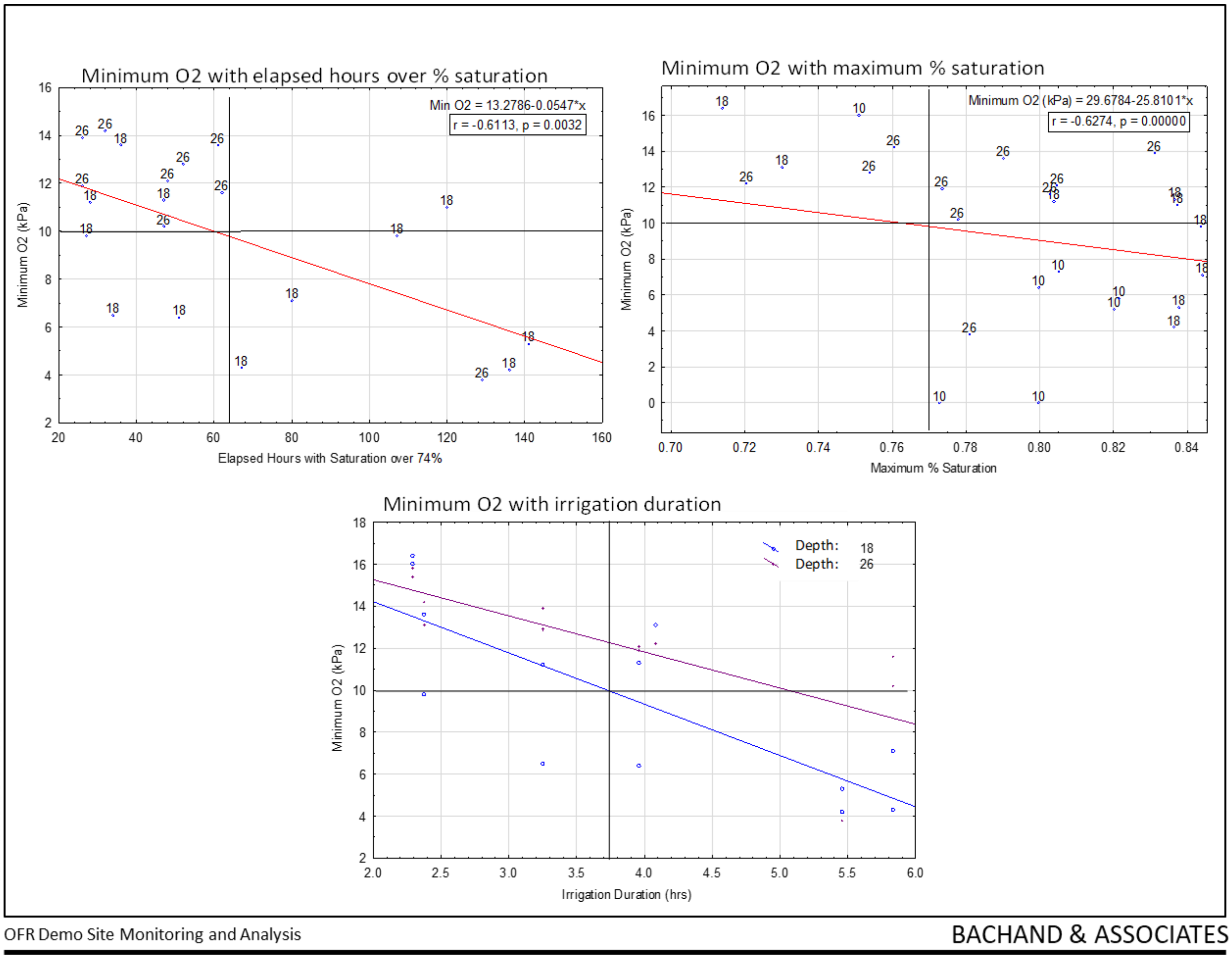
Recommendations to Growers

It will be difficult for farmers to predict soil oxygen levels. The above proposed model suggests farmers' decisions can affect soil oxygen levels. Each crop has a unique root depth and distribution, affecting respiration and oxygen consumption through the profile. Surface water depth, flood and drip water application duration, and water application intensity affect oxygen diffusive pathways through effects on available pore volume and pore connectivity. Plant dormancy and growth affect respiration rates that in turn affect soil oxygen consumption rates.

Figure 7 and Figure 8 summarize data for some of the identified drivers of low soil oxygen (i.e. elapsed hours past 74% saturation trigger, maximum percent saturation, water application duration). From these relationships and the analyses presented here, we make the following recommendations to avoid or limit oxygen conditions below 10 kPa:

- Avoid standing water for longer than 3 to 4 days on one check at one time
- Avoid percent saturation greater than 77%. This percent saturation is about 7% higher than FC and so is likely to often occur when water is moving through the soil profile. This condition may be difficult to avoid during recharge.
- Time above 74% (slightly above FC) exceeding 3 days will increase chances of oxygen levels dropping below 10 kPa.
- Review of VWC rise in soil moisture meter may indicate nature of oxygen depletion in soil. At a depth of 10 inches, VWC increasing on average greater than 0.2 per hour may indicate oxygen is dropping rapidly and more likely to drop below 10 kPa. For mid-depth soils (18 and 26-inch depth), an increase in VWC of 0.14 or more per hour may indicate that oxygen levels are dropping rapidly and more likely to drop below 10 kPa.

Measuring these variables may be difficult for many growers. If possible, past experiences in flood irrigation to meet crop needs may prove useful guidelines in developing an OFR program because these practices have not had harmful effects on crops and plant health in the past. Using this type of methodology, apply water on a portion of a field (i.e. checks) for a few days or hours, then apply water to the next check. Allow soil to drain before starting the next water application on a check.



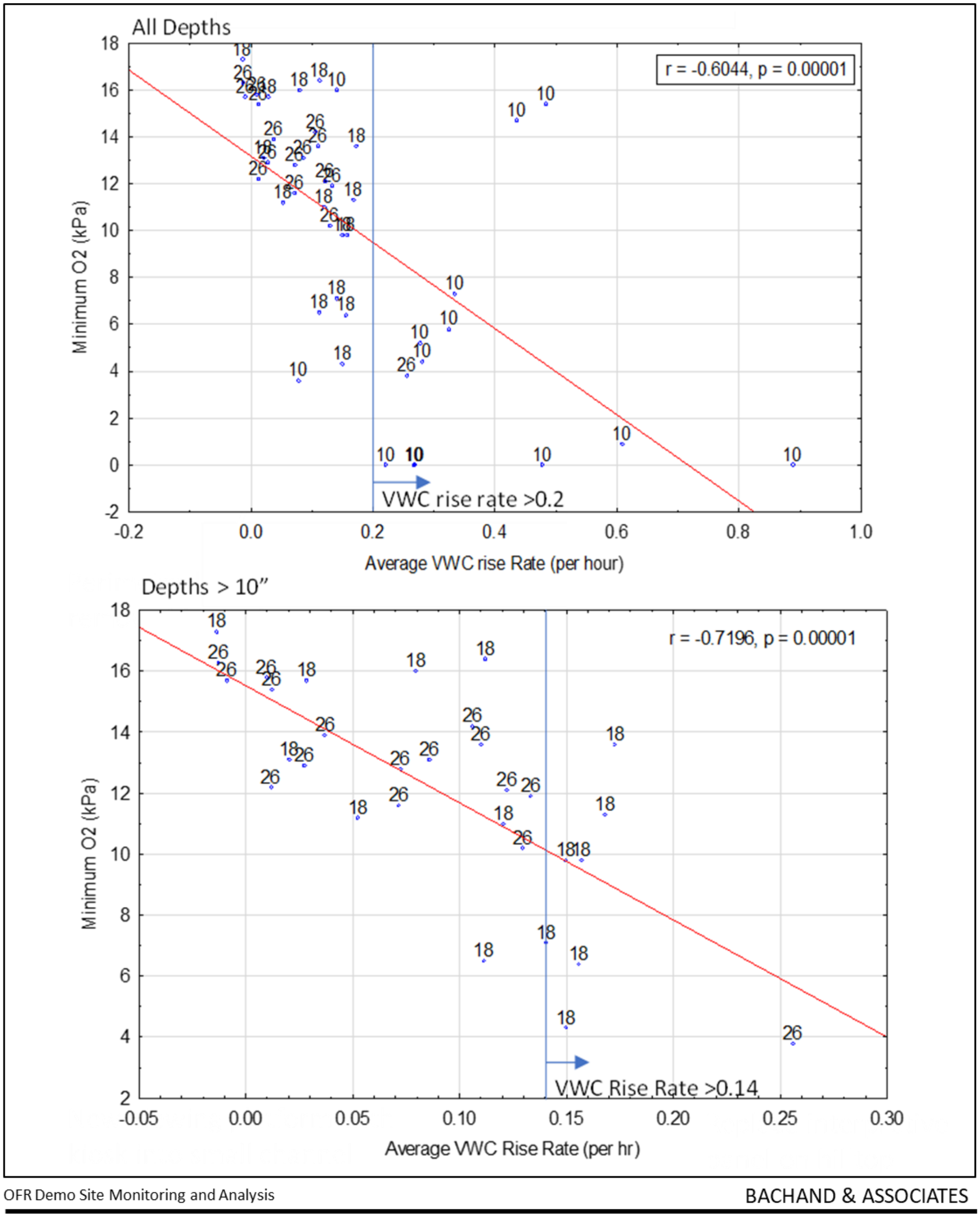
Minimum O2 with elapsed hours over % saturation

Minimum O2 with maximum % saturation

Minimum O2 with irrigation duration

Note: Numbers shown on graphs indicate soil depth in inches.

Figure 7. Relationships between minimum oxygen and correlated variables (below 10 in)



Note: Numbers shown on graphs indicate soil depth in inches.

Figure 8. Relationships between minimum oxygen and VWC rise rate.

Lessons Learned

The present study reemphasized a number of important lessons about field research.

First, it is important to install equipment well ahead of planned recharge events. Even in the normal course of business, there will always be unexpected delays related to installation, as observed here. Thus, building in buffer time during the setup phase is essential. That was highlighted with the huge, unexpected volumes of water that became available in 2017, when this study was conducted. In order to capture that water and monitor the effects, the team had to rush installation.

Second, studies on commercial farms are invaluable, but they also come with their own pitfalls, including communication. As seen with the present study, clearly communicating which plots should be used for recharge versus business as normal was essential. If possible, it might even be better to use separate fields to simplify the process.

Third, care should be taken about how to place monitoring equipment. In the study, data collection was interrupted at times due to accidents during necessary commercial field operations. Installing the equipment early on, prior to a wet year, may give the grower and staff more time to determine how to accommodate the field operations with monitoring equipment locations.

Fourth, field monitoring of recharge can only be conducted in years when sufficient surface water is available. The uncertainty about water availability can delay research for several years. Calibration and condition of monitoring equipment declines with time and will require additional time and cost to ensure consistent monitoring between years. Also, the seasonal timing of water availability for recharge may differ from year to year, further compounding the variables associated with crop respiration and other weather conditions.

Limitations and Suggestions for Future Research

The present study did not examine the potential effects of OFR on plant health, in the short- or long-term. The purpose of studying oxygen was to begin to understand potential impacts to crop health when practicing OFR. Study of the plant health over a longer time period is needed before preliminary conclusions can be drawn, as currently only one year of data was analyzed.

Similarly, we see need for further study of the dynamics of soil oxygen in relation to water application on cropland. That is especially true as California wrestles with the importance of maintaining and even replenishing groundwater supplies, using various tools and methods, including OFR.

The fate of the water applied for recharge was not evaluated for the study. However, the North San Joaquin Water Conservation District hired a local engineering firm to conduct a groundwater fate study, independent from this study, at AC-GR-R and AC-GR-C shortly after the 2018 recharge events. The preliminary results of that study show that the water recharged at this site traveled away from the nearby Mokelumne River (Personal communication with Daniel DeGraf at Provost and Pritchard, January 2019). Nonetheless, the fate of the water after it infiltrates past the root zone is not always known and the rate at which recharged water will reach an aquifer is seldom known for deep aquifers. A method to predict the fate of water quickly and broadly would be an important tool for developing on-farm recharge strategies.

The study only examined the physical and chemical aspects of soil water movement, changes to salinity, and oxygen content. Biological processes, such as microbial respiration and plant oxygen demand, were not monitored. These biological dynamics could have important implications associated with on-farm recharge and would be worth investigating in future studies. Similarly, research into specific recharge tolerances for specific species and rootstocks would be worthwhile. Additional research is needed on the ways that recharge may affect plant stress and the resulting disease or yield impacts. The complexity of correlating these affects may also be compounded by crop genetic variation and other environmental conditions.

Conclusion

The rates of recharge are possible to predict, though further confirmation of accuracy would be helpful. It is not clear from the data how recharge affects salinity, at least based on VIC data. It is possible that VIC is not the best measure for salinity changes due to recharge. Similarly, the soil drainage class does not always line up with real recharge experiences, so those ratings should be used as a guideline tempered with the grower's knowledge of the land. Overall, the OFR was able to move volumes of water from surface supplies into the soil; where that water goes afterwards, however, was not evaluated in this study.

The results of the soil oxygen analyses are not able to provide a simple rule of thumb or algorithm describing the relationship between soil oxygen levels and soil moisture. We analyzed several variables (e.g. surface water temperature, soil texture, percent saturation, initial saturation, surface water depth) as drivers triggering soil oxygen response and declines. Neither surface water temperature nor soil texture showed correlations to soil oxygen, though that may be due to relatively similar temperatures and soil textures recorded through this study. Maximum surface water depth correlated with minimum oxygen levels for all depths and season.

Absent a simple algorithm, we have provided a conceptual model of soil oxygen levels, transport, and consumption during a recharge event as a hypothesis:

- Surface water prevents surface diffusion of oxygen into the soil profile.
- Pore volume moisture reduces pore connectivity and thus oxygen diffusion.
- Reduced oxygen in the pore space provides feedback to the plant, reducing “local” respiration rates by the plant.
    - Soil microbe respiration, however, has a higher resistance to low oxygen levels, with respiration tending to increase with VWC.

This conceptual model reveals that farmer recharge management decisions can affect soil oxygen levels in the root zone. Selected crops affect root depth and distribution, affecting respiration and oxygen consumption through the profile. Floodwater application depth, flood and drip application duration, and their intensity affect oxygen diffusive pathways through effects to available pore volume and pore connectivity. Plant dormancy and growth affect respiration rates that affect soil oxygen consumption rates.

Guidelines to help farmers implementing an OFR program to minimize conditions that could lead to low soil oxygen levels:

- Avoid standing water at a given check of more than 3 to 4 days
- Limit the time in which percent saturated, calculated from soil porosity, and VWC exceed 74% for more than 3 days and avoid percent saturation greater than 77%
- Use the rate of change in VWC to identify irrigation cycles more likely to result in soil moisture conditions below 10 kPa.
- Use past, successful flood irrigation methods for meeting crop needs as reasonable guidelines for developing an OFR program.

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